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Columbia River Temperature Assessment
Simulation Methods
EPA Region 10

INTRODUCTION

Portions of the main stem of Columbia River from the International Border, (Columbia River Mile 745.0) to the mouth at Astoria, Oregon and the Snake River from Lewiston, Idaho (Snake River Mile 139.9) to its confluence with the Columbia River are designated as water quality limited for water temperature under Section 303(d) of the Clean Water Act (Fig. 1). This designation arises from an analysis of data (Washington DOE, 1998) showing these waters do not meet water quality standards for water temperature during all or part of the year. Sources which may contribute to changes in the temperature regime of these segments of the Columbia and Snake Rivers include:

(1) Construction of impoundments for hydroelectric facilities and navigational locks which increase the duration of time waters of the Columbia and Snake are exposed to high summer temperatures and which change the thermal inertia of the system

(2) Hydrologic modifications to the natural river system to generate electricity, provide irrigation water for farmlands and to facilitate navigation.

(3) Modifications of watershed from agricultural and silviculture practices which reduce riparian vegetation, increase sediment loads and change stream or river geometry.

(4) Point sources with thermal discharges.

The objective of this work is to assess the relative importance of these sources with respect to changes in the temperature regime of the main stem Columbia River in Washington and Oregon and in the Snake River in Washington. This assessment will be part of the analytical framework and decision support system for developing management strategies to attain water quality standards and protect beneficial water uses in these rivers.

GEOGRAPHY, CLIMATE AND HYDROLOGY OF THE COLUMBIA BASIN

Geography

The Columbia River drains more than 259,000 square miles of southeastern British Columbia in Canada and the Pacific Northwest states of Idaho, Oregon, Washington and Wyoming. The Columbia River rises in the Rocky Mountain Trench and flows more than 400 miles through the rugged, glaciated mountains of southeastern British Columbia before it reaches the U.S.-Canada border near Castlegar, B.C. The Columbia River enters the U.S from the Okanogan Highland Province, a mountainous, area of Precambrian-early Paleozoic marine sediments. The Columbia crosses the western margin of the Columbia Basin, a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt and flows south across the state of Washington. Near Pasco, Washington and the confluence with the Snake River, the Columbia turns west, forming the border between the states of Oregon and Washington and flows more than 300 miles through the Casacade Mountain range to the Pacific Ocean near Astoria, Oregon.

The Snake River rises in Jackson Lake in the Teton Mountains of Wyoming at an elevation of 7000 and at Snake River Mile. It flows east across the Snake Plain, which is also a broad, arid plateau formed by Miocene lava flows of the Columbia Basalt. At the western boundary of the State of Idaho it turns north and flows through a deeply incised canyon, emerging near Lewiston, Idaho. At Lewiston, the Snake joins the Clearwater River and flows west through the Palouse Country of eastern Washington, joining the Columbia near Pasco, Washington. In addition to the Clearwater, major tributaries of the Snake in Idaho include the Bruneau, Owyhee, Boise, Payette, Weiser and Salmon Rivers.

In addition to the Snake River, the Columbia's largest tributary, other major tributaries include the Kootenai, Clark Fork-Pend Oreille, Spokane, Deschutes and Willamette Rivers. The Kootenai lies largely in Canada, but flows through western Montana, northern Idaho and back into Canada before entering the Columbia below Lower Arrow Lake in B.C. The Clark Fork-Pend Oreille has its headwaters on the Continental Divide in Montana, flows through northern Idaho into Pend Oreille Lake and becomes the Pend Oreille River. The Pend Oreille River flows north into Canada before joining with the Columbia River. The Flathead, Blackfoot and Bitteroot Rivers are all major tributaries of the Clark Fork. The Spokane River begins in Lake Coeur d'Alene in Idaho and flows west through eastern Washington, entering the Columbia in Lake Franklin D Roosevelt (Lake FDR). Both the Deschutes and Willamette River have their headwaters in Oregon, the Deschutes rising in central Oregon and flowing north across lava flows of the Columbia Basalt, while the Willamette River begins in the Cascade Mountains, flows west to the Willamette Valley, then north to join the Columbia near Portland, Oregon.

Climate

The climate of most of the Columbia River drainage is primarily of continental character, with cold winters and hot, dry summers. Precipitation varies widely depending primarily on topographic influences. The interior Columbia Basin and Snake Plain generally receive less than 15 inches of precipitation annually, while in some of the mountainous regions of Canada the annual precipitation can exceed 100 inches per year.

Air temperature also varies considerably, depending on location. Summertime temperatures in the Columbia Basin and Snake Plain exceed 100^{o} F for extended periods. Temperatures at higher elevations remain cooler. Winters are cold throughout the basin and heavv precipitation falls in the form of snow in the mountain. The snowpack accumulates throughout the winter months as a result of frequent passage of storm systems from the Pacific Ocean. Some of the snowpack is incorporated into the extensive system of glaciers in the basin. However, beginning in May and June, much of the snowpack begins to melt giving rise to a hydrograph typical of a snowmelt regime.

West of the Cascade Mountains, which includes the lower 150 miles of the Columbia River and all of the Willamette River, the climate has a more maritime character. Winter air temperatures at lower elevations are seldom below freezing and summer air temperatures are seldom above 100^{o} F for long periods. Average annual precipitation west of the Cascades is greater than 40 inches in most areas. Coastal stations are typically higher. Below about 5000 feet, most of the precipitation falls as rain with 70 percent or more falling between October and March.

Hydrology

Although the hydrology of the Columbia River system has been modified by the construction of numerous hydroelectric, irrigation, flood control and transportation projects, the hydrograph still has the characteristics of a snowmelt regime. Streamflows are low during the winter, but increase beginning in spring and early summer as the snowpack melts. Melting of the winter snowpack generally takes place in May and June, and streamflows increase until the snowpack can longer support high flows. Flows then recede gradually during the summer and flows are derived from reservoir storage and from ground water recession into the fall and winter.

Occasionally, runoff from winter storms augments the base flow and river discharge can increase rapidly. This is particularly true of the Willamette River, which occasionally reaches flood stage even with flood control available from system reservoirs.

Mean monthly and mean annual river discharges for key locations on the main stem Columbia and Snake River and selected tributaries are shown in Table XX.

WATER RESOURCES DEVELOPMENT

The Columbia River and its tributaries have been developed to a high degree. The only segment of the Columbia River which remains unimpounded is the Hanford Reach between Priest Rapids Dam (Columbia River Mile 397.1) and the confluence with the Snake River (Columbia River Mile 324.3). The 11 main stem hydroelectric projects in the U.S., from Grand Coulee Dam to Bonneville Dam, develop approximately 1,240 feet of the 1,290 feet of hydraulic head. Hydroelectric and flow control projects on the main stem of the Columbia River and its tributaries in Canada have resulted in significant control of flow in the Upper Columbia and Kootenai River Basins. The Snake River is also nearly fully developed with a total of 19 dams on the main stem as well as a number of impoundments on tributaries.

These dams and reservoirs serve many purposes, including irrigation, navigation, flood control, municipal and industrial water supply, recreation and generation of hydroelectric power. There are approximately seven million acres of irrigated farmlands in the Columbia River Basin, including 3.3 million acres in Idaho, 0.4 million acres in Montana, 1.9 million acres in Washington and 1.3 million acres in Oregon (DOE, 1994). The systems has a capacity for generating more than 20,000 megawatts of hydroelectric energy and slack-water navigation now extends from the mouth at Astoria, Oregon to Lewiston, Idaho, a distance of more than 460 river miles.

In the U.S., the ownership of the dams in the Columbia River Basin includes Federal agencies, private power companies, and public utility districts. The Columbia Treaty between the United States and Canada provides the basis for managing transboundary issues related to the operation of dams and reservoirs on the Columbia River system in Canada.

WATER QUALITY ISSUES

Water quality issues in the Columbia River Basin reflect the diversity and complexity of the system. Although the quality of water is relatively high in most of the main stem Columbia, beneficial uses of aquatic resources in the Columbia River Basin are impaired in many segments due to point source pollutant loading from industries and municipalities and nonpoint source loadings from timber harvest, agriculture, mining and urban runoff. Modification of the hydrologic regime and alterations of riparian and terrestrial areas have also contributed to water quality degradation throughout the system.

The nature of water quality problems in the main stem Columbia and Snake Rivers in Washington is described in the list of water quality-limited segments prepared by The State of Washington's Department of Ecology. This list was prepared as part of the review of water quality under Section 303 (d) of the Clean Water Act, which requires that each state identify those waters within its boundaries for which water quality standards and beneficial uses are not being attained. In those segments listed under this section, the state is required to establish a total maximum daily load (TMDL) for those pollutants contributing to the impairment of beneficial uses. The listing of these water quality parameters in Water Resource Inventory Areas (WRIA's) comprising the main stem Columbia and Snake Rivers in the State of Washington is given in

Table xx. In addition, a TMDL has been established on the main stem Columbia and Snake Rivers to control dioxin, an organic toxicant associated primarily with pulp mills that use chlorine to bleach paper products.

Many of parameters on the Candidate 1998 Section 303 (d) List are associated with the operation of hydroelectric facilities and nonpoint source pollution from mining and agriculture. Two of the most frequently occurring parameters on the list are total dissolved gas and water temperature. According to the Columbia River System Operation Review (BPA et al, 1994), water released over spillways of dams can increase the level of dissolved gas in the water, which in turn causes gas bubble disease in fish. The System Operation Review also notes that dams modify the temperature regime of natural rivers. Changes in temperature and gas pressure of water released from hydroelectric projects have an impact on the aquatic ecosystem of the Columbia River system, particularly on migrating salmon and steelhead. Mortality rates for these species increase with increasing water temperatures and dissolved gas levels. This is important because several species and sub-species of salmon and steelhead in the Columbia River system have been listed as threatened or endangered under the Endangered Species Act (ESA).

Understanding the dynamics and predicting levels of total dissolved and water temperature is essential for attaining water quality standards and protecting beneficial uses in the Columbia River. A great deal of scientific effort has been devoted to this task in the Columbia River system, as well as in other aquatic environments. However, these efforts have not, as yet, been put in the context of a TMDL, as required for water bodies listed as water quality limited under Section 303 (d) of the Clean Water Act.

STUDY OBJECTIVES

One of the first steps in developing a TMDL is an assessment of the problems associated with a given water quality parameter(s). The purpose of an assessment is to identify the sources for the water quality parameter of concern and what, if any, control or management strategies are possible. In this study, water quality models for water temperature are used to provide some of the framework for a problem assessment of the main stem Columbia from the International Boundary to Bonneville Dam and of the Snake River from its confluence with the Clearwater River near Lewiston, Idaho to its confluence with the Columbia River near Pasco, Washington.

Barnwell and Krenkel (1982) have characterized the use of water quality models as management decision support tools in the context of screening, planning, and design (Barnwell and Krenkel, 1982). In their taxonomy, screening models are used to satisfy the requirement for rapidly assessing either an extensive geographical area or a large number of water quality parameters. The output of screening models is for the purpose of identifying marginal and critical areas for additional study.

The objectives of this study are to develop and implement a mathematical model of water temperature for the Columbia and Snake Rivers in a way that is generally consistent with those of the screening model, at least in terms of the level of certainty required for the model output. That is, the output from the water temperature models will be used to identify critical areas for additional analysis. However, given the geographical scale and complex nature of the hydrologic and meteorologic environment of the Columbia River system, the study objectives require a level of spatial and temporal complexity which is greater than for the screening models described by Barnwell and Krenkel (1982). In addition, effort will be devoted to quantifying the uncertainty of model output.

MATHEMATICAL MODEL DEVELOPMENT

System Boundaries

The boundaries of the Columbia River system included in the assessment of water temperature, as described previously, include the Columbia River from the International Border (R.M. 745.0) to Bonneville Dam (R.M. 145.5) and the Snake River from its confluence with the Clearwater River near Lewiston, Idaho (R.M. 139.9) to its confluence with the Columbia River near Pasco, Washington. With the exception of Grand Coulee Dam and its impounded waters, Lake FDR, all the hydroelectric projects on these segments of the Columbia and Snake Rivers have limited storage capacity and are operated as run-of-the-river reservoirs. Run-of-the-river reservoirs are those for which reservoir elevation is kept more or less constant and water coming in to the reservoir is passed directly through the reservoir. Reservoir elevations in Lower Granite Reservoir and John Day Reservoir, the two largest run-of-the-river reservoirs on the Snake and Columbia Rivers,respectively, are shown in Figures xx and xx. Because of its large storage capacity (Table XX), Lake FDR is used for flood control as well as for irrigaton and generation of hydroelectric power. Reservoir elevations for Lake FDR show a substantial annual variation (Figure XX).

The differences between the run-of-the-river reservoirs and Lake FDR, with respect to both their mode of operation and storage capacity, give rise to differences in their respective thermal regimes. For the the run-of-the-river reservoirs, the spatial variability of temperature within a cross-section perpendicular to the direction of flow is generally less than 1^0 C (McKenzie and Laenen, 1998). In Lake FDR, vertical variations in water temperature of up to 5^0 C(??) have been observed (Keith Underwood ???) at various locations along the longitudinal axis of the reservoir. Because of this difference in the thermal regimes, the run-of-the-river projects can be modeled as systems with variability in the longitudinal direction, only. Lake FDR, however, will be treated as a system with both vertical and longitudinal spatial variability. This report describes the thermal energy model for the run-of-the-river reservoirs, while development and implementation of the thermal model for Lake FDR is discussed in Whilden and Yearsley (1998).

The system boundaries for the model of the run-of-the-river segments are from the tailwaters of Grand Coulee Dam (Columbia R.M. 596.6) to Bonneville Dam (Columbia R.M. 145.5) and from Snake R.M. 139.0 to Snake River 0.0. Only the main stems are included specifically in the analysis of these segments. However, the advected thermal energy from major sources tributary (Table XX) to these segments is included in the analysis.

Thermal Energy Budget

The thermal energy budget method has proven to be a useful concept for simulating temperatures in aquatic environments. Concern regarding the impact of reservoir operations on water temperature and aquatic ecosystems provided the motivation for early applications of the method (Burt, 1958; Delay and Seaders, 1966; Rafael, 1962).(Edinger et al., 1974; Jobson, 1973; Peterson and Jaske, 1968). Prior to the passage of the Clean Water Act, numerous studies of the thermal discharges by the electric power industry were also performed using the energy budget method (Peterson and Jaske, 1968; Jobson, 1973; Edinger et al, 1974). Brown (1969, 1970) applied the method to simulating stream temperature increases resulting from the removal of riparian vegetation during logging operations. Recent applications of the energy budget method have focussed on water quality planning issues related to reservoir operations (Cole and Buchak (1995), watershed management (Risley, 1997; Yeh, 19??; Rishel et al, 1982; Sinokrot and Stefan, 1993) and fisheries habitat enhancement (Bartholow, 1989; Theurer et al, 1984).

Thermal energy budget models for aquatic ecosystems are developed either in an Eulerian frame of reference, in which the reference system is fixed in space and through which the water flows; or a Lagrangian frame of reference in which the reference system moves with the fluid. The one-dimension thermal energy model for estimating the state variable, water temperature, stated in terms of the Eulerian viewpoint and assuming there is no longitudinal dispersion is:

(1)

where,

ρ = the density of water, kg/meter^3,

C_p = the specific heat capacity of water, kcal/deg C/kg,

A_x = the cross-sectional area of the river at the distance, x, meter^2,

T = the water temperature, deg C,

Q = the river flow rate, meter^3/second,

w_x = the width of the river at the distance, x, meters,

H_{net} = the heat flux at the air-water interface, kcal/meter^2/second,

S_{adv} = the heat advected from tributaries and point sources, kcal/meter/second,

w_T = a random water temperature forcing function, $\sim N(0, \Sigma_T(t))$

x = the longitudinal distance along the axis of the river, meters,

t = time, seconds.

In the Lagrangian frame of reference the one-dimensional thermal energy model, the systems model for estimating the water temperature, assuming no longitudinal dispersion, is given by:

(2)

where the symbols are as previously defined.

Eqs. (1) and (2) are the state-space system equations for water temperature in the Eulerian and Lagrangian frame of references, respectively. Water temperature measurements also provide an estimate of the system state and the observation model for water temperature is given by (Gelb, 1974)

$$z_k = H_k T + v_k \tag{3}$$

where,

z_k = the measured value of the water temperature, ^oC,

H_k = the measurement matrix,

v_k = the measurement error, $\sim N(0, \Sigma_z(t))$

Heat Exchange Across The Air-Water Interface

Heat exchange across the air-water interface is often the major source of thermal energy for lakes, rivers and reservoirs. As is the case for the applications described above, this study assumes the net exchange of thermal energy, H_{net}, across the air-water interface can be described by:

$$H_{net} = (H_s - H_{rs}) + (H_a - H_{ra}) + H_{evap} + H_{cond} - H_{back} \tag{4}$$

where,

H_{net} = Net heat exchange across the air-water interface, kcal/meter^2/second,

H_s = Shortwave solar radiation, kcal/meter^2/second,

H_{rs} = Reflected shortwave solar radiation, kcal/meter^2/second,

H_a = Longwave atmospheric radiation, kcal/meter^2/second,

H_{ra} = Reflected atmospheric radiation, kcal/meter^2/second,

H_{evap} = Evaporative heat flux, kcal/meter^2/second,

H_{cond} = Conductive heat flux, kcal/meter^2/second,

H_{back} = Blackbody radiation from the water surface, kcal/meter^2/second.

The specific form for each of these terms, as used in this and most other studies involving the energy budget method, is based on a compilation of heat budget studies by Wunderlich and Gras (1967). Chapra (1997) and Bowie et al (1985) also have comprehensive discussions of each of the terms in Eq. (3) adapted from Wunderlich and Gras (1967).

Solution Method

The goal of the solution method is to obtain an optimal estimate of the state variable, water temperature. The Kalman filter (Gelb, 1974; Schweppe, 1974) provides a recipe for combining state estimates from a linear systems model (Eq. (1) or Eq. (2)) with estimates from the observation model (Eq. (3)) to give the best linear unbiased estimate of the system state. When there are measurements available, the recipe calls for obtaining a solution to the systems model and combining the solution with the observation. The two estimates are combined using a weighting factor determined by the relative uncertainty of the systems model compared to the uncertainty of the observation model. The weighting factor, the so-called Kalman gain matrix, is derived by constraining the error in the estimate to be unbiased and to have a minimum mean square error.

To obtain an estimate of the water temperature from the systems model, it is first necessary to decide whether to implement the solution method with a Lagrangian point of view or with an Eulerian point of view. Given the spatial and temporal complexity of the natural environment, most mathematical models using the thermal energy budget method are developed in the Eulerian frame of reference. The Eulerian frame of reference is a more intuitive way of viewing changes in concentrations simply because most measuring devices are fixed at a specific location rather than moving with the water. It is also less difficult to incorporate spatial complexity into the Eulerian framework, and, therefore, easier to add more spatial dimensions as well as more complex spatial processes such as dispersion and turbulent diffusion.

Most systems models using the Eulerian framework solve Eq. (1) with either finite difference (Brown and Barnwell, 1987; Cole and Buchak, 1995; Sinokrot and Stefan, 1993; Smith, 1978) or finite element methods (Baca and Arnett, 1976). These models have generally proved valuable for simulating water temperatures in a variety of aquatic environments. However, it is well known that solutions to equations of the type characterized by Eq. (1), using finite difference or finite element techniques, are subject to stability and accuracy problems (e.g., O'Neill, 1981). For water quality models, stability problems are generally not as serious as accuracy problems. When a solution becomes unstable, it is usually quite obvious and easy to fix. Accuracy problems are more pervasive and often subtle. Of particular concern to developers of finite difference and finite element methods are problems associated with the propagation of phenomena with short wavelengths. They are most evident in the propagation of sharp spatial gradients when advection dominates the system. The resulting simulations can have spurious damping of high frequencies or oscillations. They are caused by differences between the rate at which the numerical scheme propagates the solution in space and the rate at which the solution would be propagated in space by the natural system.

Solution techniques based on the Lagrangian point of view (Jobson, 1981) avoid the accuracy problems associated with Eulerian methods but lack the computational convenience of a fixed grid. However, efficient accurate solution methods have been proposed which combine the virtues of each point of view (Cheng et al, 1984; Yeh, 1990; Zhang et al, 1993). In these hybrid Eulerian-Lagrangian methods, advective processes are treated with a Lagrangian formulation. Diffusion processes are treated with an Eulerian formulation. Valocchi and Malmstead (1992) have shown that operator splitting of this kind can provide accurate solutions to advection-diffusion-reaction problems when the reaction term is sufficiently small.

Although diffusion-like processes are being neglected in this analysis, the mixed Eulerian-Lagrangian method was chosen as the solution technique for simulating water temperature in the Columbia River system for the following reasons:

- It provides flexibility to expand scope of model to include diffusion-like processes and/or more spatial dimensions.

- It is relatively easy to avoid nstabilities in the solution when the Courant stability criterion is exceeded.

- It reduces the state-estimation (filtering and prediction) problem to one of a single state variable rather than one requiring a state variable for each finite difference or finite element grid point.

- Mixed Lagrangian-Eulerian schemes carry a lower computational burden than upwind methods.

The mixed Eulerian-Lagrangian method used in this study uses the concept of reverse particle tracking to implement the Lagrangian step. The river system is divided into N segments, not necessarily of the same spatial dimensions. Within each segment, however, the geometric properties of the river system are assumed to be constant during a given time step. Water temperature values are recorded only on the boundaries between segments. As an example of the method, consider the Segment J. (Figure XX). At the end of a computational time step, t = $T_{n+1,}$ a particle at the downstream end of the Segment J, is flagged. The flagged particle is tracked upstream until its position at the beginning of the time step, t = T_n, is located. The location of a particle tracked in this manner will, in general, not be precisely on a segment boundary, where water temperatures are stored by the computational scheme. Therefore, it is necessary to determine the water temperature of the particle at the beginning of the time by interpolating between the points where water temperatures are recorded. In the solution technique used in this study, this is accomplished with a second-order polynomial using Lagrangian interpolation (Press et al, 1986) as shown in Figure XX. Once the location of the particle and its initial water temperature are determined for the beginning of the time step, the particle is followed back downstream to its location at the end of the time step (the downstream end of Segment J). The change in water temperature for the particle during this time step is estimated using Eq. (2).

The information required to obtain a solution to Eq. (2) using reverse particle tracking includes

- River width as a function longitudinal distance during the time step
- Cross-sectional area as a function of longitudinal distance during the time step
- River velocity as a function of longitudinal distance during a time step
- Net heat exchange as a function of longitudinal distance during a time step.

The hydraulic characteristics of the unimpounded reaches of the river system are estimated from power equations relating mean velocity, depth and width (Leopold and Maddock, 1953). That is,

(5)

(6)

(7)

where,

U = the river velocity, feet/second,

D = the river depth, feet,

W_x = the river width, feet,

The coefficients, A_u, B_u, A_d, A_u, B_u, A_w, and B_w, are estimated by simulating river hydraulics conditions under various flow conditions using the methods of steady gradually varied flow (HEC, 1995). The gradually varied flow method gives estimates of U, D, and W_x as a function of river flow. The coefficients are determined by fitting Eqs. (4-6) to the resulting estimates using the method of least squares.

For the impounded reaches, the water surface elevation is assumed to remain constant, such that the depth and width remain constant at any cross-section and the velocity, U, is simply

$$U = Q/(W_x{*}D) \tag{8}$$

Exchange of thermal energy across the air-water interface is estimated from Eq. (3) using formulations for components of the heat budget as described by WRE (1968).

Time and Length Scales

To accomplish the management objectives of the analysis it is necessary to simulate daily-averaged water temperatures as a function of longitudinal distance in the Columbia and Snake Rivers. This establishes an approximate lower limit on system time scales and on data requirements. Stability and accuracy issues associated with solutions to Eq. (3) can impose a requirement of even smaller time increments to obtain reliable solutions. However, the simulated results for time scales less than a day are valuable only in terms of their contribution to the solution accuracy. Since the time scale of the input data is equal to or greater than one day, there can be no physical significance to these higher (computationally-generated) frequencies. In an effort to include the environmental variability due to hydrology and meteorology, the largest time scales are of the order of two decades. This time scale is constrained by the hydrologic data available for the Columbia River system under existing managment. Existing management in this case means operation of the system subsequent to the construction of the last hydroelectric project (Lower Granite, 197)

The length scales for the analysis are determined by a number of factors. These include the availability of geometric data, spatial variability in the river geometry and computational stability and accuracy. It is often the case that data availability provides the most severe constraint. However, in the case of the Columbia and Snake Rivers, within the boundaries of this analysis, there is ample data for describing river geometry in both rivers. The primary factor determining the length scale of this analysis is the need to achieve stable, accurate solutions. Length scales are such that the time it takes a parcel of water to traverse a given computational segment is always equal to or less than one day. For the Columbia and Snake Rivers, this results in length scales of the order of ?? to ?? miles.

Rationale for Approach

Idealizing the largest part of the Snake and Columbia River system in terms of a one-dimensional model is based on the assumption that a simple model will capture the major features of the water temperature regime in the two large rivers. This is in keeping with the management objective of providing a primary temperature assessment for developing a TMDL. The simple one-dimensional model described above is relatively easy to implement. Based on previous work in the Columbia and Snake Rivers (Rafael, 1962; Yearsley, 1969; Jaske and Synoground, 1970), a simple model of this type should capture the major features of water temperature impacts in this system. The mixed Lagrangian-Eulerian scheme for handling advection was chosen based on studies such as those done by Yeh (1990) and Zhang et al

(1993)

DATA SOURCES

Water Temperature

The extensive water temperature data records for the Columbia and Snake River have been assembled and reviewed for quality by Tony Laenen and Stuart McKenzie (Laenen and McKenzie, 1998). In addition, Laenen and McKenzie (1998) organized the data in electronic formats for rapid analysis. The results of their work provide a water temperature data set for the Columbia and Snake Rivers which can be used to describe temperature model uncertainty. The data quality analysis performed by Leanen and McKenzie (1998) provides a basis for characterizing the uncertainty associated with the measurements.

McKenzie and Laenen (1998) compiled data only for the main stem Columbia and Snake Rivers. Temperature data for the tributaries included in the analysis (Table XX) were obtained from observations made by the Idaho Power Company, Washington State Department of Ecology (DOE) and the U.S. Geological Survey (USGS). The location of monitoring locations, period of record and frequency of analysis are shown in Table XX.

River Geometry

River geometry is needed to characterize the hydraulic properties of the river as a function of flow and time.   The basic data required is elevation of the river channel above mean sea level at a sufficient number of cross-sections so as to adequately describe water depth, water width and velocity as a function of river flow. A number of sources were used to accomplish this. These sources are described in Table 1.

Hydrology

River hydrology data for the main stem Columbia and Snake Rivers, as well as the major tributaries, were obtained from the records maintained by the U.S. Geological Survey. Gaging stations used in the study are shown in Table XX.

Meteorology

Meteorologic data, including station pressure, cloud cover, wind speed, air temperature and relative humidity, are required for the thermal energy budget calculations. Stations in the Columbia basin with these data include Lewiston, Idaho (222222),
Spokane, Washington (232323) and Yakima, Washington (242424). Data are available for these locations at three-hour intervals from the NCDC SAMSON data sets. The period of record for each of these stations is shown in Table 3.

Stations with maximum and minimum daily air temperatures are more numerous and are included in the NCDC Local Climatological Data Sets. Air temperature data from these stations were used in conjunction with the regional meteorological stations (Table 3) to develop synthetic records on a local scale. Stations used for this purpose and the period of record are shown in Table 4.

PARAMETER ESTIMATION

Hydraulic Coefficients

As described above, the hydraulic properties of each unimpounded river segment are estimated from relationships of the type given in Eq. (4) - (6. One of the primary objectives of the study is to assess the impact of impoundments. It was, therefore, necessary to make estimates of these coefficients for two states of the system, one with dams in place and for one with all the dams removed. For the case in which the dams were in place, the results from the USACE HEC-5Q model of the Columbia and Snake Rivers were provided by Nancy Yun of the USACE North Pacific Division Office. The only impounded reach under the present configuration of impoundents is the Hanford Reach. The coefficients in Eqs. (XX) - (XX) for the Hanford Reach are given in Table A-1, Appendix A. The geometric characteristics of the impoundments for this scenario are also taken from the US Army Corps of Engineers' HEC-5Q model and are given in Table A-2.

For the scenario with dams removed, geometric properties of the Columbia and Snake Rivers, obtained from the sources given in Table XX, were used as input data to HEC-RAS (HEC, 1995), the steady gradually varied flow model developed by the US Army Corps of Engineers Hydrologic Engineering Center. Surface elevations of the Columbia and Snake Rivers were estimated for flows of 150,000, 250,000 and 500,000 cfs in the Columbia River and 60,000, 120,000 and 240,000 cfs in the Snake River. For each of these flows, the average water depth, surface width and velocity at selected locations was used to estimate the coefficients in Eqs (5)-(7) using the methods of least squares. The coefficients obtained in this manner are given in Table A-3, Appendix A.

Water Balance

The daily flow at any location in either river was determined from the sum of the daily gaged flow of the main stem headwaters and the tributaries upstream from the location. This assumes that

- information regarding flow changes are transmitted instantaneously to locations downstream.

- tributary sources other than those shown in Table XX are negligible.

The simulated flow, using these assumptions, is compared to the flow measured at various USGS gages in Figure XX.

Heat Budget

The individual terms of the heat budget (Eq. 4) are estimated using relationships given in WRE (1968) and are based on the work of Wunderlich and Gras (1967)

<u>Shortwave (Solar) Radiation</u>

$$(H_s - H_{rs}) = F(\Phi, \delta, D_y)$$

<u>Longwave (Atmospheric) Radiation</u>

$$(H_a - H_{ra}) = (1-\alpha_{ar})\ 1.23 \times 10^{-16}\ (1.0 + 0.17\ C^2)\ (T_{DB} + 273.)^6$$

Evaporative Heat Flux

$H_{evap} = \rho * \lambda * E_v * W * (e_o - e_a)$

Conduction Heat Flux

Black Body (Water Surface) Radiation

$H_{back} = 0.97\ \sigma\ (T_s + 273.)^4$

Initial Water Temperatures

Daily water temperatures are not always available for the locations used as initial conditions on the main stem Columbia and Snake Rivers or for the input conditions for important tributaries (Table zz). For most stations long-term sampling with a period of two to four weeks provides sufficient data to synthesize stream temperatures using air temperature. Mohseni et al (1998) found that a nonlinear model of the type:

(??)

where, T_s is the weekly stream temperature, T_a is the weekly air temperature from a nearby weather station and α, β, γ and μ are determined by regressing the observed water temperature data onto the air temperature data. Separate functions of the type defined in Eq. (??) are used to describe the rising limb and the falling limb. In their study of 584 USGS stream gaging stations within the contiguous United State, Mohseni et al (1998) concluded that the method was accurate and reliable at 89% of the streams. Mohseni et al (1998) also found that the method gives good results even when the air temperature measurements were not in proximity to the stream gaging locations. Some adjustments were made to the method by constraining certain parameters in Eq. ( ). The resulting parameters for both rising and falling limbs, for each of the input locations is given in Table XX.

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ERROR PROPAGATION ALGORITHM

System Model: $\underline{x}_k = f_{k-1}\,\underline{x}_{k-1} + \underline{w}_{k-1}$ $\quad \underline{w}_k \sim N(\underline{0}, Q_k)$

Measurement Model: $\underline{z}_k = H_k\,\underline{x}_k + \underline{v}_{k-1}$ $\quad \underline{V}_k \sim N(\underline{0}, R_k)$

State Estimate Extrapolation: $\underline{x}_k(-) = f_{k-1}\,\underline{x}_{k-1}(+)$

Error Covariance Extrapolation: $P_k(-) = f_{k-1}\,P_{k-1}(+)f_{k-1} + Q_{k-1}$

State Estimate Update: $\underline{x}_k(+) = \underline{x}_k(-) + K_k[\underline{z}_k - H_k\,\underline{x}_k(-)]$

Error Covariance Update: $P_k(+) = [I - K_k H_k] P_k(-)$

Kalman Gain Matrix: $K_k = P_k(-)H_k^T[H_k P_k(-)H_k^T + R_k]^{-1}$